Advanced Functional Materials 2018 vol.28 N33

Ferromagnet/Superconductor Hybridization for Magnonic Applications

Golovchanskiy I., Abramov N., Stolyarov V., Bolginov V., Ryazanov V., Golubov A., Ustinov A.
Kazan Federal University, 420008, Kremlevskaya 18, Kazan, Russia

Abstract

© 2018 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim In this work, a new hybridization of superconducting and ferromagnetic orders is demonstrated, promising for magnonics. By measuring the ferromagnetic and spin wave resonance absorption spectra of a magnetostatically coupled permalloy/niobium bilayer at different temperatures, magnetostatic spin wave resonances with unconventional dispersion are observed. The mechanism behind the modified dispersion, confirmed with micromagnetic simulations, implies screening of the alternating magnetostatic stray fields of precessing magnetic moments in the ferromagnetic layer by the superconducting surface in the Meissner state.

http://dx.doi.org/10.1002/adfm.201802375

Keywords

ferromagnetic resonance, magnonics, spin waves, superconducting Meissner state, superconductor/ferromagnet hybrids

References

[1] S. S. Saxena, P. Agarwal, K. Ahilan, F. M. Grosche, R. K. W. Haselwimmer, M. J. Steiner, E. Pugh, I. R. Walker, S. R. Julian, P. Monthoux, G. G. Lonzarich, A. Huxley, I. Sheikin, D. Braithwaite, J. Flouquet, Nature 2000, 406, 587.

[2] D. Aoki, J. Flouquet, J. Phys. Soc. Jpn. 2012, 81, 011003.

[3] G. S. Thakur, G. Fuchs, K. Nenkov, Z. Haque, L. C. Gupta, A. K. Ganguli, Sci. Rep. 2016, 6, 37527.

[4] S. Nandi, W. T. Jin, Y. Xiao, Y. Su, S. Price, D. K. Shukla, J. Strempfer, H. S. Jeevan, P. Gegenwart, Th. Bruckel, Phys. Rev. B ,2014 ,89 .014512

[5] V. S. Stolyarov, I. S. Veshchunov, S. Yu Grebenchuk, D. S. Baranov, I. A. Golovchanskiy, A. G. Shishkin, N. Zhou, Z. X. Shi, X. F. Xu, S. Pyon, Y. Sun, W. Jiao, G. Cao, L. Ya Vinnikov, A. A. Golubov, T. Tamegai, A. I. Buzdin, D. Roditchev, Sci. Adv. 2018, https://doi.org/10.1126/sciadv.aat1016.

[6] Y. A. Genenko, A. Usoskin, H. C. Freyhardt, Phys. Rev. Lett. 1999, 83, 3045.

[7] A. V. Pan, S. X. Dou, J. Appl. Phys. 2004, 96, 1146.

[8] M. Lange, M. J. Van Bael, Y. Bruynseraede, V. V. Moshchalkov, Phys. Rev. Lett. 2003, 90, 197006.

[9] S. Haindl, M. Weisheit, T. Thersleff, L. Schultz, B. Holzapfel, Supercond. Sci. Technol. 2007, 21, 045017.

[10] A. I. Buzdin, Rev. Mod. Phys. 2005, 77, 935.

[11] I. F. Lyuksyutov, V. L. Pokrovsky, Adv. Phys. 2005, 54, 67.

[12] V. V. Ryazanov, V. A. Oboznov, A. Y. Rusanov, A. V. Veretennikov, A. A. Golubov, J. Aarts, Phys. Rev. Lett. 2001, 86, 2427.

[13] A. A. Golubov, M. Y. Kupriyanov, E. Ilichev, Rev. Mod. Phys. 2004, 76, 411.

[14] J. Linder, J. W. A. Robinson, Nat. Phys. 2015, 11, 307.

[15] A. K. Feofanov, V. A. Oboznov, V. V. Bolginov, J. Lisenfeld, S. Poletto, V. V. Ryazanov, A. N. Rossolenko, M. Khabipov, D. Balashov, A. B. Zorin, P. N. Dmitriev, V. P. Koshelets, A. V. Ustinov, Nat. Phys. 2010, 6, 593.

[16] A. V. Ustinov, V. K. Kaplunenko, J. Appl. Phys. 2003, 94, 5405.

[17] I. V. Vernik, V. V. Bol'ginov, S. V. Bakurskiy, A. A. Golubov, M. Y. Kupriyanov, V. V. Ryazanov, O. Mukhanov, IEEE Trans. Appl. Supercond. 2013, 23, 1701208.

[18] S. V. Bakurskiy, N. V. Klenov, I. I. Soloviev, V. V. Bol'ginov, V. V. Ryazanov, I. V. Vernik, O. A. Mukhanov, M. Kupriyanov, A. A. Golubov, Appl. Phys. Lett. 2013, 102, 192603.

[19] I. A. Golovchanskiy, V. V. Bolginov, V. S. Stolyarov, N. N. Abramov, A. B. Hamida, O. V. Emelyanova, B. S. Stolyarov, M. Y. Kupriyanov, A. A. Golubov, V. V. Ryazanov, Phys. Rev. B ,2016 ,94 .214514

[20] L. R. Tagirov, Phys. Rev. Lett. 1999, 83, 2058.

[21] J. Gu, C.-Y. You, J. S. Jiang, J. Pearson, Y. B. Bazaliy, S. D. Baden, Phys. Rev. Lett. 2002, 89, 267001.

[22] D. Stamopoulos, E. Aristomenopoulou, Sci. Rep. 2015, 5, 13420.

[23] R. R. Gaifullin, R. G. Deminov, L. R. Tagirov, M. Yu. Kupriyanov, A. A. Golubov, Physics of the Solid State 2017, 59, 2114.

[24] E. C. Gingrich, B. M. Niedzielski, J. A. Glick, Y. Wang, D. L. Miller, R. Loloee, W. P. Pratt Jr., N. O. Birge, Nat. Phys. 2016, 12, 564.

[25] M. Weides, M. Kemmler, H. Kohlstedt, R. Waser, D. Koelle, R. Kleiner, E. Goldobin, Phys. Rev. Lett. 2006, 97, 247001.

[26] S. V. Bakurskiy, V. I. Filippov, V. I. Ruzhickiy, N. V. Klenov, I. I. Soloviev, M. Yu. Kupriyanov, A. A. Golubov, Phys. Rev. B 2017, 95, 094522.

[27] J. Wang, M. Singh, M. Tian, N. Kumar, B. Liu, C. Shi, J. K. Jain, N. Samarth, T. E. Mallouk, M. H. W. Chan, Nat. Phys. 2010, 6, 389.

[28] A. Y. Aladyshkin, A. V. Silhanek, W. Gillijns, V. V. Moshchalkov, Supercond. Sci. Technol. 2009, 22, 053001.

[29] J. E. Villegas, S. Savel'ev, F. Nori, E. M. Gonzalez, J. V. Anguita, R. García, J. L. Vicent, Science 2003, 302, 1188.

[30] M. Vélez, J. I. Martín, J. E. Villegas, A. Hoffmann, E. M. González, J. L. Vicent, I. K. Schuller, J. Magn. Magn. Mater. 2008, 320, 2547.

[31] C. C. de Souza Silva, A. V. Silhanek, J. V. de Vondel, W. Gillijns, V. Metlushko, B. Ilic, V. V. Moshchalkov, Phys. Rev. Lett. 2007, 98, 117005.

[32] D. P. de Lara, M. Erekhinsky, E. M. Gonzalez, Y. J. Rosen, I. K. Schuller, J. L. Vicent, Phys. Rev. B ,2011 ,83 174507.

[33] A. Gomez, E. M. Gonzalez, M. Iglesias, N. Sanchez, F. J. Palomares, F. Cebollada, J. M. Gonzalez, J. L. Vicent, J. Phys. D: Appl. Phys. 2013, 46, 095302.

[34] C. Carballeira, V. V. Moshchalkov, L. F. Chibotaru, A. Ceulemans, Phys. Rev. Lett. 2005, 95, 237003.

[35] Q. H. Chen, C. Carballeira, V. V. Moshchalkov, Phys. Rev. B ,2009 ,79 .104520

[36] M. Lange, M. J. V. Bael, A. V. Silhanek, V. V. Moshchalkov, Phys. Rev. B ,2005 ,72 .052507

[37] C. L. S. Lima, C. C. de Souza Silva, Phys. Rev. B ,2009 ,80 .054514

[38] Z. Yang, M. Lange, A. V., R. Szymczak, V. V. Moshchalkov, Nat. Mater. 2004, 3, 793.

[39] A. Rusanov, M. Hesselberth, J. Aarts, A. I. Buzdin, Phys. Rev. Lett. 2004, 93, 057002.

[40] V. G. Veselago, Sov. Phys. Usp. 1968, 10, 509.

[41] A. Pimenov, A. Loidl, P. Przyslupski, B. Dabrowski, Phys. Rev. Lett. 2005, 95, 247009.

[42] S. E. Barnes, M. Aprili, I. Petkovic, S. Maekawa, Supercond. Sci. Technol. 2011, 24, 024020.

[43] S. Mai, E. Kandelaki, A. F. Volkov, K. B. Efetov, Phys. Rev. B ,2011 ,84 .144519

[44] I. A. Golovchanskiy, N. N. Abramov, V. S. Stolyarov, O. V. Emelyanova, A. A. Golubov, A. V. Ustinov, V. V. Ryazanov, Supercond. Sci. Technol. 2017, 30, 054005.

[45] H. Huebl, C. W. Zollitsch, J. Lotze, F. Hocke, M. Greifenstein, A. Marx, R. Gross, S. T. B. Goennenwein, Phys. Rev. Lett. 2013, 111, 127003.

[46] I. A. Golovchanskiy, N. N. Abramov, V. S. Stolyarov, I. V. Shchetinin, P. S. Dzhumaev, A. S. Averkin, S. N. Kozlov, A. A. Golubov, V. V. Ryazanov, A. V. Ustinov, J. Appl. Phys. 2018, 123, 173904.

[47] Y. Zhu, A. Pal, M. G. Blamire, Z. H. Barber, Nat. Mater. 2017, 16, 195.

[48] A. A. Golubov, M. Y. Kupriyanov, Nat. Mater. 2017, 16, 156.

[49] M. Rubinstein, P. Lubitz, W. E. Carlos, P. R. Broussard, D. B. Chrisey, J. Horwitz, J. J. Krebs, Phys. Rev. B ,1993 47, 15350.

[50] C. Bell, S. Milikisyants, M. Huber, J. Aarts, Phys. Rev. Lett. 2008, 100, 047002.

[51] O. A. Chivileva, A. G. Gurevich, I. A. Lineichuk, S. G. Shul'man, S. O. Fregatov, Tech. Phys. Lett. 2000, 26, 949.

[52] T. Muhge, N. N. Garif'yanov, Y. Goryunov, K. Theis-Brohl, K. Westerholt, I. A. Garifullin, H. Zabel, Physica C 1998, 296, 325.

[53] Magnonics: From Fundamentals to Applications (Eds: S. O. D emokritov, A. N. Slavin), Springer-Verlag, Berlin/Heidelberg 2013.

[54] D. Stancil, Theory of Magnetostatic Waves, Springer-Verlag, New York, Inc. 1993.

[55] V. V. Kruglyak, S. O. Demokritov, D. Grundler, J. Phys. D: Appl. Phys. 2010, 43, 264001.

[56] A. V. Chumak, A. A. Serga, B. Hillebrands, J. Phys. D: Appl. Phys. 2017, 50, 244001.

[57] Y.-C. Chen, D.-S. Hung, Y.-D. Yao, S.-F. Lee, H.-P. Ji, C. Yu, J. Appl. Phys. 2007, 101, 09C104.

[58] N. Alvarez, G. Alejandro, J. Gomez, E. Goovaerts, A. Butera, J. Phys. D: Appl. Phys. 2013, 46, 505001.

[59] C. Bayer, J. Jorzick, B. Hillebrands, S. O. Demokritov, A. N. Slavin, N. Gorn, M. P. Kostylev, Spin Dynamics in Confined Magnetic Structures III, Springer, Berlin/Heidelberg 2006, pp. 57–103.

[60] A. A. Serga, A. V. Chumak, B. Hillebrands, J. Phys. D: Appl. Phys. 2010, 43, 264002.

[61] C. Kittel, Phys. Rev. 1958, 100, 1295.

[62] M. H. Seavey, P. E. Tannenwald, J. Appl. Phys. 1959, 30, S227.

[63] T. G. Rappoport, P. Redliński, X. Liu, G. Zaránd, J. K. Furdyna, B. Jankó, Phys. Rev. B ,2004 ,69 .125213

[64] Y. V. Khivintsev, L. Reisman, J. Lovejoy, R. Adam, C. M. Schneider, R. E. Camley, Z. J. Celinski, J. Appl. Phys. 2010, 108, 023907.

[65] P. Deorani, J. H. Kwon, H. Yang, Curr. Appl. Phys. 2014, 14, S129.

[66] M. Donahue, D. Porter, OOMMF User's Guide, Version 1.0, Interagency Report NISTIR 6376, National Institute of Standards and Technology, Gaithersburg, MD 1999.

[67] J. E. Miltat, M. J. Donahue, Handbook of Magnetism and Advanced Magnetic Materials, Vol. 2, JohnWiley & Sons, Ltd. 2007.

[68] K. Kawasaki, H. Takagi, M. Umeno, IEEE Trans. Microwave Theory Tech. 1974, 22, 924.

[69] T. Yukawa, J. Ikenoue, J. Yamada, K. Abe, J. Appl. Phys. 1978, 49, 376.

[70] M. Vroubel, B. Rejaei, J. Appl. Phys. 2008, 103, 114906.

[71] I. S. Maksymov, M. Kostylev, J. Appl. Phys. 2013, 113, 043927.

[72] M. Mruczkiewicz, M. Krawczyk, J. Appl. Phys. 2014, 115, 113909.

[73] I. Neudecker, G. Woltersdorf, B. Heinrich, T. Okuno, G. Gubbiotti, C. Back, J. Magn. Magn. Mater. 2006, 307, 148.

[74] I. A. Golovchanskiy, V. V. Bolginov, N. N. Abramov, V. S. Stolyarov, A. B. Hamida, V. I. Chichkov, D. Roditchev, V. V. Ryazanov, J. Appl. Phys. 2016, 120, 163902.